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Bond strength and development length of steel bar in unconfined self-consolidating concrete

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ABSTRACT

There are no specific models for evaluating bond strength and development length of steel bar in unconfined self-consolidating concrete (SCC). Existing equations for steel bar embedded in normal concrete are not efficient and applicable for SCC. So, it is essential to introduce more precise and efficient models. In this study, pull out tests of referenced literatures are used to present new predicting equations. Unlike existing equations, proposed models demonstrate acceptable fit with the database. Also, in order to evaluate the accuracy of the proposed models, direct pull out tests are performed in this study. The results of experimental test are in good agreement with those obtained by proposed new models.

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1. Introduction

Recent researches have been concerned with improving properties of various concrete mixtures at fresh and hardened state. Self-consolidating concrete (SCC) is a new type of concrete mixture, which has been considered to improve the properties of fresh concrete for cast-in-place and precast applications. Workability and flowability are the most important properties of self-consolidating concrete, which allow to flow in the all spaces of formwork under its own weight without any vibration equipment. Also, greater volume of fine aggregates and flowability of SCC have improved the passing ability of mixture especially where congestion of reinforcement occurs. Reduction of the coarse aggregate content, using different type of admixtures and adding fillers to mixture like limestone powder are the important difference between SCC and NC.

Until now, many researches have been performed to study the bond strength of steel bar in SCC. Dehn et al. [1] have studied the time development of the bond behavior of steel rebar in SCC. Sonebi et al. [2] have performed a comparative study of normal concrete (NC) and self-consolidating concrete (SCC). They have reported that the bond strength in SCC is 10–40% higher than NC. Chan et al. [3] have reported that SCC has higher bond strength relative to normal concrete. Esfahani et al. [4] have shown that normal concrete and self-consolidating concrete have the same bond strength for bottom cast bars. Foroughi-Asl et al. [5] have performed a comparative study between SCC and NC. They have reported that the bond strength is higher in SCC specimens as compared with normal concrete. Castel et al. [6] have conducted experimental tests to study the possible differences between bond and cracking properties of SCC and vibrated concrete. Heirman et al. [7] have performed experimental investigations concerning the shrinkage and creep behavior of limestone powder type SCC mixtures. Their studies have shown that SCC mixtures have higher shrinkage and creep deformations compared with the traditionally vibrated concrete mixture. Floyd et al. [8] have performed experimental investigation to examine the bond of prestressed strand with self-consolidating concrete. Helincks et al. [9] have carried out experimental test to investigate the bond and shear performance of powder-type self-consolidating concrete. They have reported that SCC shows normalized characteristic bond strength values higher than vibrated concrete. Also, many investigations have been done to determine the structural behavior of large-scale self-consolidating concrete members [10,11].

Two types of tests, small-scale and large-scale, have been considered in the specifications to determine the bond strength between concrete and steel reinforcing bar. The direct pull out test and the beam-end pull out test are the common small-scale tests of

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Nomenclature

A_b	area of reinforcing bar: mm^2
A_{st}	area of stirrups including all legs: mm^2
A_{st1}	area of one leg of the stirrup: mm^2
All	amount of all aggregates: kg/m^3
$C_{\min}$	minimum concrete cover: mm
$C_{\max}$	maximum concrete cover: mm
COV	coefficient of variation
d_b	bar diameter: mm
E	empirical constant
E_s	elastic modulus of steel rebar: GPa
f_c	characteristic strength of concrete: MPa
$Fine$	amount of fine aggregate: kg/m^3
f_y	yield strength of rebar: MPa
f_{yt}	yield strength of stirrup: MPa
f_u	ultimate strength of rebar: MPa
G	empirical constant
$HRWR$	high-range water-reducing admixture (super plasticizer)
$I_{0,1,2,3}$	empirical constants
IAE	integral absolute error
K	empirical constant
K_{st}	effect of confinement by stirrup in literatures
K_{tr}	effect of confinement by stirrup (ACI 318-08)
L	embedded length
l_d	development length: mm
$LWSCC$	lightweight self-consolidating concrete
M	empirical factor
n	number of bars being spliced
NC	normal concrete
q	empirical constant
SCC	self-consolidating concrete
S_{st}	spacing of stirrups: mm
W/C	water-to-cement ratio
α	bar location factor
β	epoxy coating factor
λ	lightweight concrete factor
γ	reinforcement size factor
τ	bond stress: MPa
$\tau_{\max}$	bond strength: MPa

bond strength. Also, beam anchorage test and the beam splice test are the two common large-scale test [12]. The direct pull out test is the most common due to the ease of fabricating. Many studies (Zhu et al. [13], De Almeida Filho et al. [14], Valcuende and Parra [15], Lachemi et al. [16], Boel et al. [17], Myers et al. [18], Pop et al. [19]) have performed direct pull out test for determining bond strength of steel bar in self-consolidating concrete. Zhu et al. [13] have reported that the bond strength of SCC is about 20–30 percent greater than conventional concrete in pull out test. De Almeida Filho et al. [14] have shown that bond strength of rebar in SCC is higher than normal concrete in the range of 5–20 percent. Valcuende and Parra [15] have reported that bond strength of SCC is about 7–17 percent greater than that of normal concrete. Lachemi et al. [16] have investigated the bond behavior of lightweight self-consolidating concrete (LWSCC).

The mixture of SCC is different from the normal concrete. Higher amounts of fine aggregate and also the superplasticizer would result in higher bond strength and apparently lower development length. Although there are different models for determining bond strength and development length of steel bar in normal concrete, they cannot evaluate the interfacial behavior of steel bar in self-consolidating concrete accurately. This study presents new models for predicting interfacial properties of steel bar–SCC interface. Also, in order to validate proposed models, a supplementary experimental test is performed in this investigation.

2. Models for bond strength and development length

2.1. New model for bond strength of steel bar in SCC

Experimental results of referenced literatures [13–19] are used to obtain reliable models. The properties and overall results of database are summarized in Table 1. Different equations for predicting bond strength between steel bar and normal concrete have been presented by researches and specifications [20–25], which are listed in Table 2. Minimum concrete cover for rebar ($C_{\min}$), diameter of rebar (d_b), characteristic strength of concrete (f_c), embedded length of rebar (L), area of stirrups including all legs (A_{st}), area of one leg of the stirrup (A_{st1}) and spacing of stirrup (S_{st}) are the important factors have been considered in predicting equations. The deviation of existing models used for normal concrete from the experimental results of pull-out test in SCC is determined by the term of integral absolute error (IAE) [25–27], and the coefficient of variation (COV). The coefficient of variation is the ratio of *experimental/theorical* and the term of integral absolute error (IAE) is given by Eq. (1) [25–27].

$$IAE = \sum \frac{\sqrt{(Experimental - Equations)^2}}{\sum Experimental} \tag{1}$$

Integral absolute error (IAE) is more sensitive than coefficient of variation (COV).

In order to attain an efficient and accurate model for bond strength of steel rebar in SCC, the form of equation presented by Wu and Zhao [25] is used which is given by Eq. (2).

$$\frac{\tau_{\max}}{\sqrt{f_c}} = \frac{G}{1 + Ee^{qK}} \tag{2}$$

where G, E, q and K are the coefficients to be determined by regression analyses. A trial-and-error based algorithm along with statistical software STATISTICA [28] is used to find a best-fit value of G, E and q. As shown in Table 2, different parameters affect the bond strength. So, an overall parameter denoted as K, has been used in the literature. Xu [21], Harajli et al. [23], and Wu and Zhao [25] introduced Eqs. (3a)–(3c) respectively to define the effective parameter, K.

$$K = 1.6 + 0.7\frac{C_{\min}}{d_b} + 20\frac{A_{st1}}{C_{\min}S_{st}} \tag{3a}$$

$$K = \frac{C_{\min}}{d_b} + 7\frac{A_{st1}}{C_{\min}S_{st}} \tag{3b}$$

$$K = \frac{C_{\min}}{d_b} + 33\frac{A_{st1}}{C_{\min}S_{st}} \tag{3c}$$

where d_b is bar diameter, $C_{\min}$ is minimum concrete cover, A_{st1} is area of each stirrup and S_{st} is spacing of transverse reinforcement. The ratio of $C_{\min}/d_b$ and $A_{st1}/C_{\min}S_{st}$ have been used as a dimensionless factor in the parameter K. However, based on the database for SCC, the following equation was found to be used in Eq. (2).

$$K = \frac{C_{\min}}{d_b} + 10\frac{d_b}{L} + K_{st} \tag{4}$$

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